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Fragmentation reactions of ^{11}Li

H. Esbensen
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

G. F. Bertsch
Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824
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We examine the effect of the spatial correlation between the valence neutrons in ^{11}Li on the cross section for (^{11}Li,^{9}Li) reactions on different targets at 800 MeV/nucleon. The correlation suppresses the nuclear part of the cross section slightly but it strongly enhances the Coulomb part compared to an independent particle description. Agreement with measurement is significantly improved.

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An important test of theoretical models of the extremely loosely bound nucleus ^{11}Li is the fragmentation cross section, in particular, the breakup reaction $^{11}\mathrm{Li}\rightarrow{}^{9}\mathrm{Li}+2n$. The first measurements [1] revealed a surprisingly large cross section for reactions on a lead target, and a substantial part was attributed to Coulomb dissociation. This implies a large dipole strength at very low excitations, and a large theoretical effort has been devoted, in recent years, to explaining and accounting for the necessary strength.

In previous publications we developed a semiquantitative three-body model for ^{11}Li, assuming it consists of two valence neutrons interacting with each other and with an inert ^{9}Li core, to study the ground state [2] and the dipole response [3]. The model predicts a weak binding and a strong dipole response of the valence neutrons quite close to threshold. However, in order to make comparisons with fragmentation data, it is also necessary to determine the nuclear part of the reactions, preferably within the same model that is used to calculate the dipole response.

In this Brief Report, we present calculations of the nuclear part of the fragmentation at 800 MeV/nucleon. The high beam energy is an advantage since the nuclear interaction with the target nucleus can be described in an eikonal approximation as an absorption, with a strength determined by the free nucleon-nucleon cross sections. We have previously applied such a model [4] to calculate the nuclear fragmentation of ^{11}Li, assuming that the two valence neutrons are independent particles. Here we use the same "diffractive" eikonal model that we used in Ref. [4] to describe the nuclear absorption, but we shall assume that the two valence neutrons are bound in the correlated ground state $\Psi_{gs}(\mathbf{r}_1,\mathbf{r}_2)$, which we determined in Ref. [2] from our three-body model. We showed there that the correlations enhance the Coulomb excitation cross section, but the nuclear fragmentation should be decreased by the correlations. The reason is that the nuclear mechanism is the absorption of the neutrons by the target. A second neutron is less effective at producing additional absorption if it is in the immediate vicinity of the first one, since the areas of target interaction would overlap.

Our calculation is based on the eikonal formula for the probability that the two valence neutrons remain in their ground state. The probability is calculated as a function of impact parameter b (with respect to a target nucleus) as

$$P_{\mathrm{val}}(b)=|\langle\Psi_{gs}(\mathbf{r}_1,\mathbf{r}_2)|e^{i\chi(|\mathbf{b}+\mathbf{r}_{1\perp}|)}e^{i\chi(|\mathbf{b}+\mathbf{r}_{2\perp}|)}|\Psi_{gs}(\mathbf{r}_1,\mathbf{r}_2)\rangle|^2 , \tag{1}$$

where $\mathbf{r}_i=(\mathbf{r}_{i\perp},z_i)$, $i=1,2$, are the positions of the two neutrons and χ is the usual eikonal phase,

$$\chi_n(b)=\frac{i}{2}\int_{-\infty}^{\infty}[\sigma_{nn}\rho_T^n(r)+\sigma_{np}\rho_T^p(r)]dz . \tag{2}$$

Here $\rho_T^{n,p}$ are the target neutron and proton densities and $r^2=b^2+z^2$. We take nucleon-nucleon cross sections as in Ref. [4], $\sigma_{nn}=\sigma_{pp}=47$ mb and $\sigma_{np}=38.5$ mb. The target densities were obtained by a simple scaling of the charge distributions measured in elastic electron scattering [5].

We calculate the overlap in Eq. (1) using the LS representation of the two-neutron wave function (which has $J=0$) and making a multipole expansion of the eikonal distortion factor. Thus we write the wave function

$$\Psi_{gs}(\mathbf{r}_1,\mathbf{r}_2)=\sum_{L=S}^{0,1}\sum_{l}\psi_l^{LS}(r_1,r_2)[[Y_l(\hat{r}_1)Y_l(\hat{r}_2)]_L|S\rangle]_{J=0} . \tag{3}$$

The eikonal distortion factor is expressed as

$$e^{i\chi(|\mathbf{b}+\mathbf{r}_{1\perp}|)}=\sum_{\lambda\mu}F_{\lambda\mu}(b,r)Y_{\lambda\mu}(\hat{r}) . \tag{4}$$

The probability amplitude is then given by

$$\langle\Psi_{gs}|e^{i\chi(|\mathbf{b}+\mathbf{r}_{1\perp}|)}e^{i\chi(|\mathbf{b}+\mathbf{r}_{2\perp}|)}|\Psi_{gs}\rangle=\sum_{L=S}^{0,1}\sum_{l_1l_2}\sum_{\lambda\mu}A(LSl_1l_2\lambda)\int dr_1dr_2\psi_{l_2}^{LS}(r_1,r_2)F_{\lambda\mu}(b,r_1)F_{\lambda-\mu}(b,r_2)\psi_{l_1}^{LS}(r_1,r_2) , \tag{5}$$

with

$$A(LSl_1l_2\lambda)=\delta_{L,S}(-1)^{L+\lambda-\mu}\frac{(2l_1+1)(2L+1)^{1/2}}{4\pi}\langle l_1 0\lambda 0|l_2 0\rangle^2\begin{Bmatrix} l_1 l_2 \lambda \\ l_2 l_1 L\end{Bmatrix} . \tag{6}$$

In order to calculate the two-neutron removal cross section, we note that ^{11}Li has only one bound state, whereas ^{10}Li is unbound. The nuclear part of this cross section is therefore

$$\sigma^N_{-2n}=\int d^2\mathbf{b}[1-P_{\rm val}(b)]P_{\rm core}(b) , \tag{7}$$

where $P_{\rm core}$ is the probability that all the core nucleons remain in their ground state. This probability is also calculated in the eikonal approximation as described in Ref. [4], and we assume for simplicity that the core nucleons can be described as independent particles bound in the single-particle potential (4.1) of Ref. [2]. Similarly, the nuclear part of the interaction cross section is

$$\sigma^N_I=\int d^2\mathbf{b}[1-P_{\rm val}(b)P_{\rm core}(b)] . \tag{8}$$

The results of the calculations described above are shown in Fig. 1 by the dashed curves (Nucl.), which is an interpolation between numerical results obtained for targets of ^{9}Be, ^{12}C, ^{27}Al, ^{63}Cu, ^{120}Sn, and ^{208}Pb. Also shown is the Coulomb dissociation cross section for the two-neutron removal channel, which was obtained from the correlated dipole response of the valence neutrons as described in Ref. [3]. The sum of the Coulomb and nuclear contributions to the two-neutron removal cross section (lower fully drawn curve) is seen to reproduce the trend of the data from Ref. [1] very well. The total interaction cross section (upper fully drawn curve) includes the nuclear part [Eq. (8)] and the two Coulomb parts associated with dipole excitations of the valence neutrons and the ^{9}Li core, which we have calculated as two independent modes of excitation.

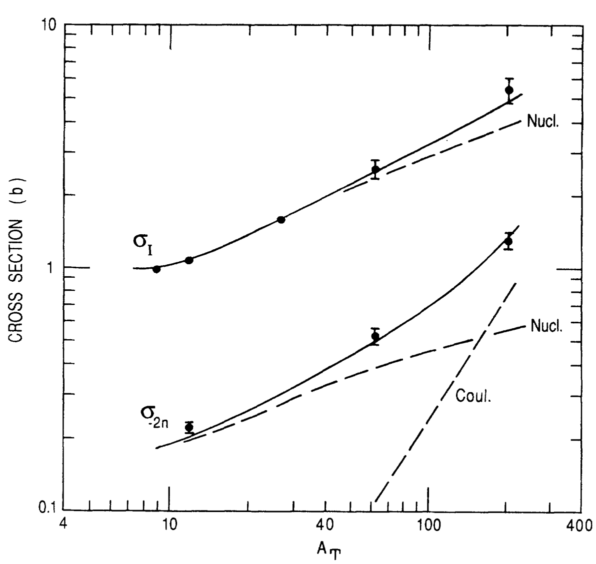

FIG. 1. Interaction cross sections (σ_I) and two-neutron removal cross sections (σ_{-2n}) for ^{11}Li at 800 MeV/nucleon as a function of the target mass. The data are from Ref. [1]. The contributions from nuclear breakup are shown by the dashed lines (Nucl.). Also shown is the contribution from Coulomb dissociation (Coul.) to the two-neutron removal.

It is interesting to compare these results with what one obtains from an independent particle description of the valence neutrons. Here we shall compare with the independent-particle model described in Ref. [2], which was adjusted to reproduce the one-neutron density we obtained in the three-body model. The advantage of comparing these two models is that any differences in the results can be attributed to the effect of the spatial correlation between the valence neutrons. The two results are compared in Table I for a lead target. We only show the results for the two-neutron removal channel, since it is more sensitive to the correlation between the valence neutrons. The interaction cross section, on the other hand, is dominated by the breakup of the core, which we assume to be the same in the two models. It is seen that nuclear part is only slightly suppressed in the three-body model compared with the independent particle model, whereas the Coulomb part is strongly enhanced. The enhancement of the latter is discussed in detail in Ref. [3] in terms of the sum rule for the total dipole strength, which clearly shows the effect of the spatial correlation. The total two-neutron removal cross sections obtained from the three-body model are consistent with the measurements. The independent-particle model, on the other hand, underpredicts the data for a heavy target, where the Coulomb dissociation plays an important role.

There are several uncertainties in the calculations. The neutron density of the target may actually be slightly higher in the surface region than we have estimated, in particular for a heavy target. Medium effects on the nucleon-nucleon interaction are expected to be small at 800 MeV/nucleon. In order to get a feeling for the sensitivity, we repeated the calculations, reducing the nucleon-nucleon cross sections by 10%. This reduced the

TABLE I. Comparison of the two-neutron removal cross sections of ^{11}Li at 800 MeV/nucleon on a lead target obtained in the independent-particle model (IPM) and from the three-body model (3BM). The first two columns show the contributions from nuclear and Coulomb breakup, respectively, and the third column is the sum. The last column also shows the measured value [1].

Model	σ^N_{2n} (mb)	σ^C_{2n} (mb)	σ_{2n} (mb)
IPM	606	519	1125
3BM	562	798	1360
Experiment			1310±100

nuclear part of the two-neutron removal cross section by 4% for the lightest target and only 1.4% for the lead target. Let us also mention that calculations of nuclear fragmentation sometimes include a finite-range interaction. An example is given in Ref. [6], where the finite-range effect enhances interaction cross sections typically by about 10%.

Our results are also sensitive to the description of the ^{9}Li core. The model we have used is described in Sec. 4.1 of Ref. [2]. It gives a ^{9}Li interaction cross section of 875 mb for a carbon target and a rms radius of 2.68 fm. These values are significantly larger than the measured cross section of 796±6 mb [7] and the rms radius of 2.32±0.02 fm, which was extracted in Ref. [8]. Let us mention that if we adjust our model to reproduce this extracted rms radius we do indeed reproduce the measured interaction cross section for ^{9}Li. The associated two-neutron removal cross section for ^{11}Li on a carbon target is actually in much better agreement with the measurement, but the total interaction cross section is now smaller than the measured value.

We do not find it imperative to improve our model of the core at this point, considering all the uncertainties involved. Among them we note that the difference $\sigma_I - \sigma_{2n}$ from the ^{11}Li measurements on carbon is 840±14 mb [1], which is somewhat larger than the measured interaction cross section for ^{9}Li. The deviation may suggest that the core of ^{11}Li is slightly different from a free ^{9}Li nucleus. A better overall fit to the ^{11}Li data (both σ_{2n} and σ_I) is obtained by adjusting the rms radius of the ^{9}Li core to 2.52 fm. Combined with the rms radius of the valence neutrons, which in our model[1] is 5.84 fm, we obtain an overall rms radius of 3.38 fm for ^{11}Li. This is only 8% larger than the value 3.12±0.16 fm, which was extracted in Ref. [8] from the fragmentation data using a Glauber-type calculation and harmonic-oscillator wave functions.

There is also some uncertainty in nuclear structure of ^{11}Li. Our model [2] predicts a two-neutron separation energy S_{2n} of 0.2 MeV when the ^{9}Li-n Hamiltonian is adjusted to produce a $p_{1/2}$ resonance at 0.8 MeV. Recent measurements [9] imply a slightly higher value for S_{2n} of 0.34±0.05 MeV, and the location of the neutron resonance in ^{10}Li is also disputed (see, for example, Ref. [10]). We have therefore repeated the calculations with a $p_{1/2}$ neutron resonance located at 0.72 MeV. This modification increases the calculated value of S_{2n} to the recently measured value of 0.34 MeV. The associated two-neutron removal cross sections are now 20% smaller than the three measurements (on C, Cu, and Pb targets). Clearly, it is important to know the structure of ^{10}Li more accurately since it is an important constraint on three-body models such as ours and that of Ref. [10].

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[1]Note that in all our calculations we ignore center-of-mass corrections to shell-model wave functions.

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